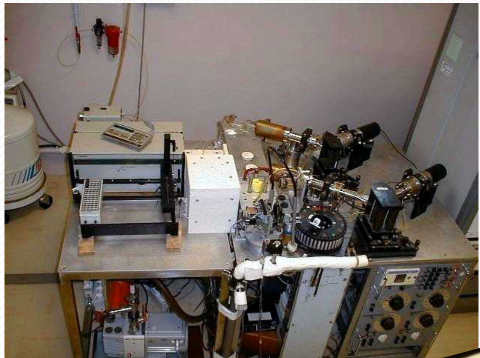
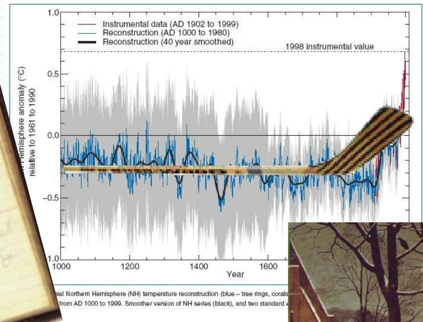
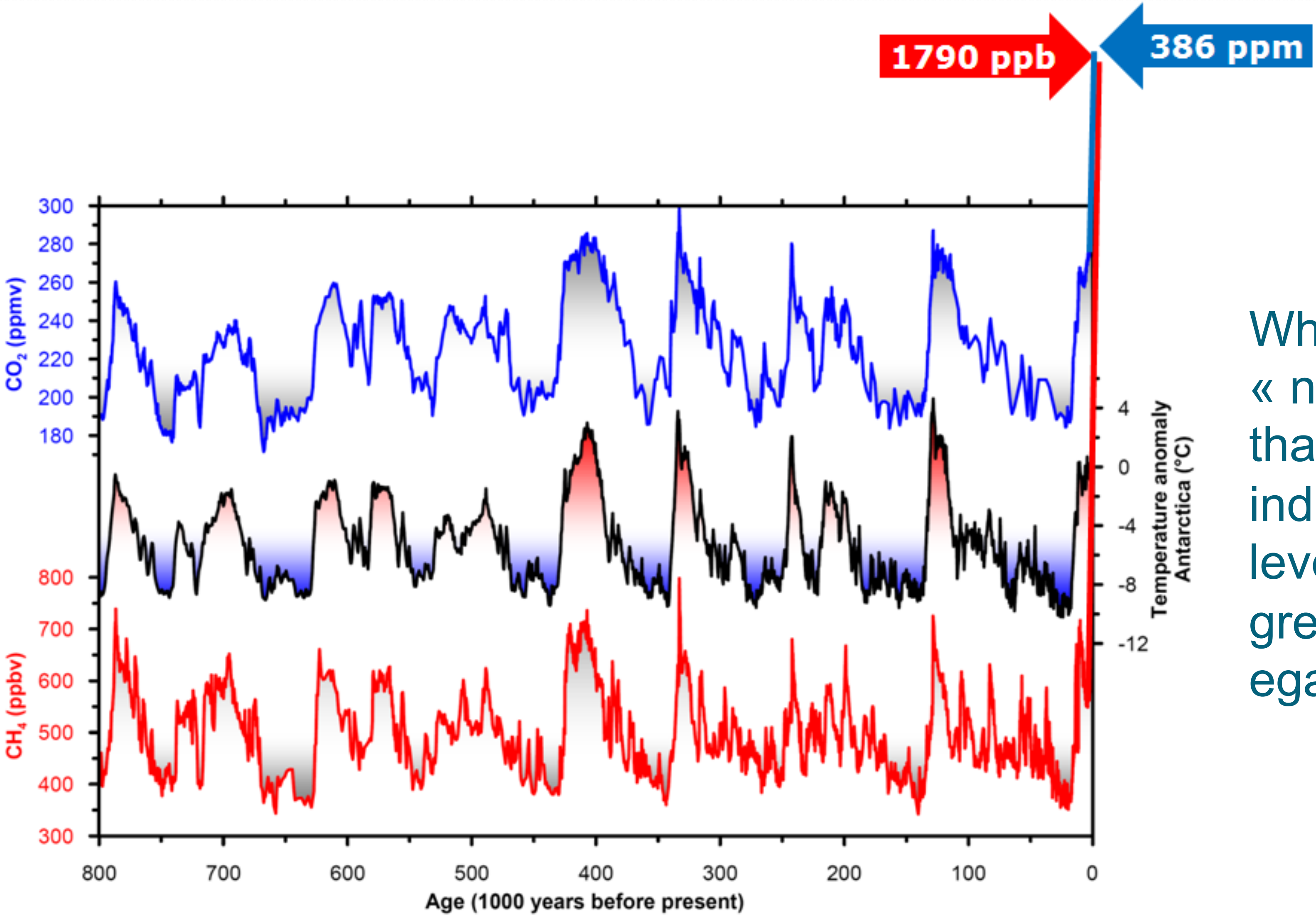
climate sensitivity from a paleo perspective - some points that will be discussed in the AR5

Georg Hoffmann IMAU - UU





What is the best equivalent?



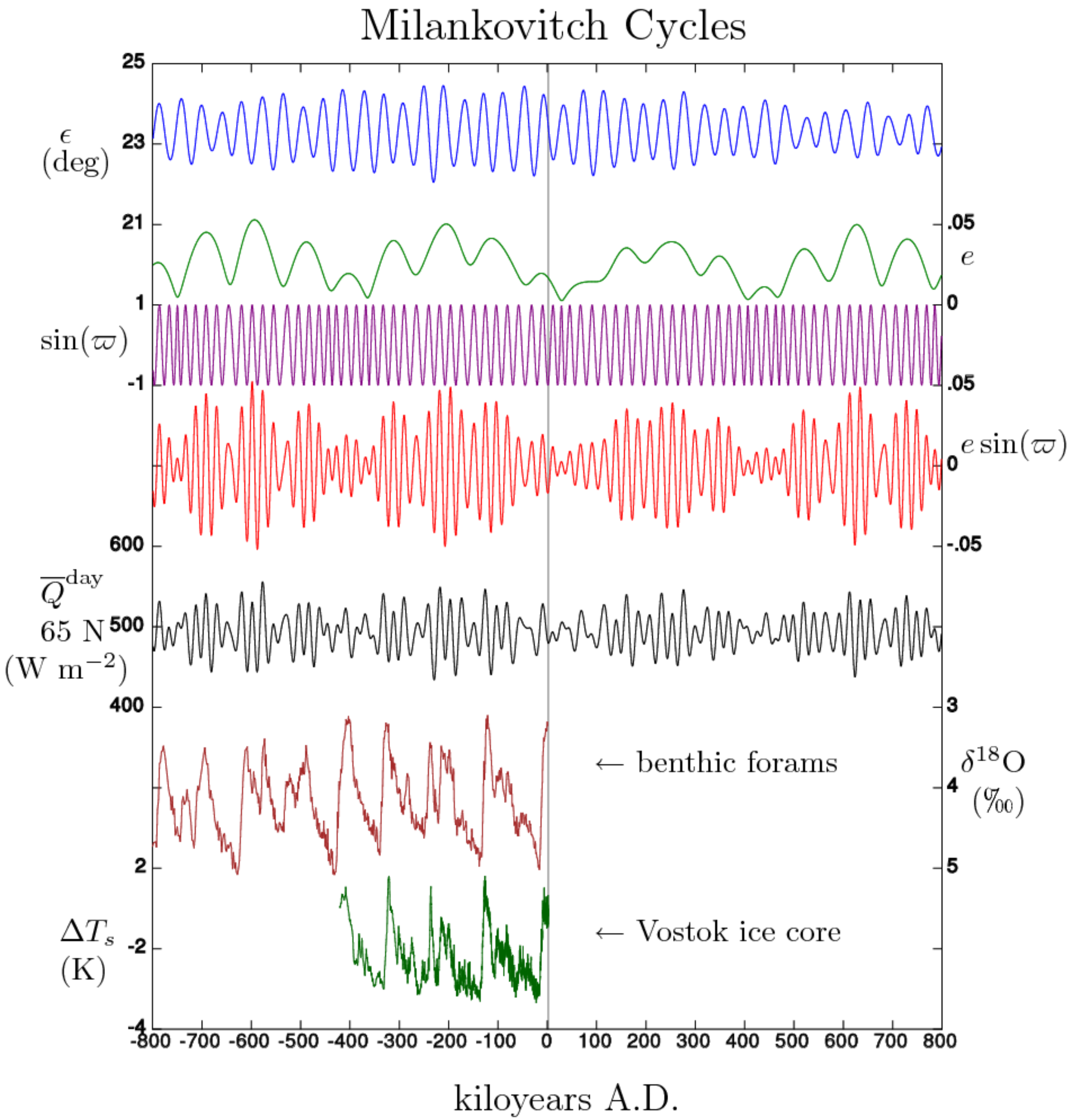
What is the « natural », that is pre-industrial level of the greenhous egases

The problem of the feedbacks

[W]ater vapor, confessedly the greatest thermal absorbent in the atmosphere, is dependent on temperature for its amount, and if another agent, as CO_2, not so dependent, raises the temperature of the surface, it calls into function a certain amount of water vapor which further absorbs heat, raises the temperature and calls forth more vapor ….

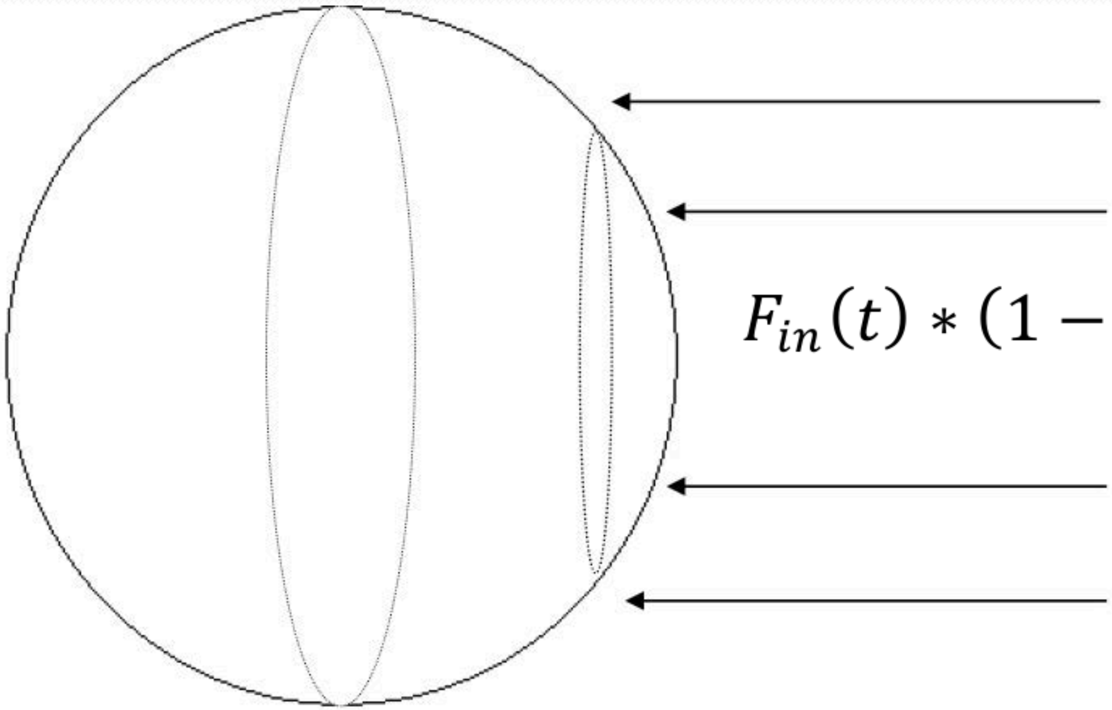
TC Chamberlin 1905

What is the best equivalent?



It's difficult to find a period which corresponds in any climatic sense to our actual time period, that is greenhouse gas levels, orbital parameters, solar activity, extension of ice sheets.

Earth Energy balance: Les chevalliers de la terre plate



$$F_{in}(t) * (1-\alpha)\pi R^2 = 4\pi R^2 \varepsilon\sigma T^4$$

Fig 1- Exposed Earth face. When sunlight strikes the Earth it comes from one direction and the planet makes a circular shadow.

F_{in}=non-constant solar constant ~1364 W/m^2

$\alpha=\alpha$(cloud, ice, snow, vegetation …)~0.3

$\varepsilon=\varepsilon$(surface type)=emissivity

$\sigma=5.67*10^{-8}$ $W/m2/K^4$ Stefan-Boltzmann constant

Computation of the effective radiative temperature

F_{in}=non-constant solar constant ~1364 W/m^2

> Claude Pouillet 1837 measured 1228W/m2 with his Pyrheliometer

$\alpha=\alpha$(cloud, ice, snow, vegetation …)~0.3

$\varepsilon=\varepsilon$(surface type)=emissivity

$\sigma=5.67*10^{-8}$ W/m2/K^4 Stefan-Boltzmann constant

Effective Radiation Temperature (in this case=blackbody temperature)=T_{eff}

$$T_{eff} = \sqrt[4]{\frac{F_{in}(1-\alpha)}{4\sigma}} \sim 255K = 0°F$$

Did Fahrenheit know about Black-Body radiation nearly 200 years before Planck?

Perturbation of the radiative equilibrium

$$C\frac{dT}{dt} = F_{in} - F_{out} = F_{in} - \sigma T^4$$

C is the heat capacity of the Earth (essentially of the ocean)
dH=change in the Earth heat content=CdT

For a more realistic planet we have however a more complicated energy balance with Fin and Fout depending on clouds, ice albedo, snow albedo, greenhouse gases, etc. etc.:

$F_{in}=F_{in}$(Sol.const.,cloud, ice, ozone, H2O,..)
$F_{out}=F_{out}$(Temp, cloud, GHG)

Definition of climate sensitivity

For equilibrium we can write:

F_{in}(Sol.Const., albedo, H_2O,…)=F_{out}(T, H_2O, log2CO_2,clouds)

Let's assume a small perturbation in the composition of CO2:

$$0 = \frac{dFout}{dlog2CO2} = \frac{\partial F_{out}}{\partial T} dT + \frac{\partial F_{out}}{\partial log2CO2} dlog2CO2$$

Strongly simplifying the full complexity of radiative transport we estimate

$$\frac{\partial F_{out}}{\partial T} = \frac{\partial(\sigma T^4)}{\partial T} = 4\sigma T^3 \sim 4W/m^2K$$

Definition of climate sensitivity

Change of radiative forcing due to a change in CO_2 concentration as a simplifying formula deduced from line-by-line radiation code (Myrhe, 1998):

$$F = 5.35 * \ln\left(\frac{C}{C_0}\right) => \frac{\partial F}{\partial log2CO2} = 5.35 * log2(e) \sim 4W/m2$$

=>

$$\frac{dT}{dlog2CO_2} = \frac{\frac{\partial F}{\partial log2CO2}}{\frac{\partial F}{\partial T}} =: \Delta_0 = 1K$$

1K warming for a CO2 doubling with clouds, H_2O, ice, snow fixed. It contains only the "Planck Feedback" which we put in the following in the Δ_O Term.

Definition of climate sensitivity

Now let's add to the Planck Feedback a "real feedback", the water feedback and assume that H2O=H2O(T) depends only on temperature.

F_{in}(Sol.Const., albedo, H_2O,…)=F_{out}(T, H_2O, log2CO_2,clouds)

$$\frac{\partial F_{in}}{\partial H_2O}\frac{dH_2O}{dT}dT = \frac{\partial F_{out}}{\partial T}dT + \frac{\partial F_{out}}{\partial H_2O}\frac{dH_2O}{dT}dT + \frac{\partial F_{out}}{\partial logCO2}dlogCO2$$

So the temperature response to CO2 changes with water vapour feedback amounts to:

$$\frac{dT}{dlog2CO_2} = \frac{\Delta_0}{1-\beta_{H2O}} \quad \text{with} \quad \beta_{H2O} = \left(-\frac{\partial F_{out}}{\partial H_2O} + \frac{\partial F_{in}}{\partial H_2O}\right)\frac{dH_2O}{dT} \Big/ \frac{\partial F_{out}}{\partial T}$$

Definition of climate sensitivity

The computation of β_{H2O} is extremely difficult (line by line radiative model assuming fixed relative humidity or a GCM).

By generalizing instead of just allowing changes in CO2 we consider any small change of the radiative dis-equilibrium dF:

$$dT = \frac{\Delta_0}{1 - \beta_{H2O}} dF$$

Δ_0 is called the Planck (or No Feedback) factor

$1/(1-\beta_{H2O})$ is the water vapour feedback.

If we add more processes i.e. feedbacks the equation changes to:

$$dT = \frac{\Delta_0}{1 - \beta_{H2O} - \beta_{LR} - \beta_{ice} - \beta_{Cloud}} dF$$

Feedback parameters from models

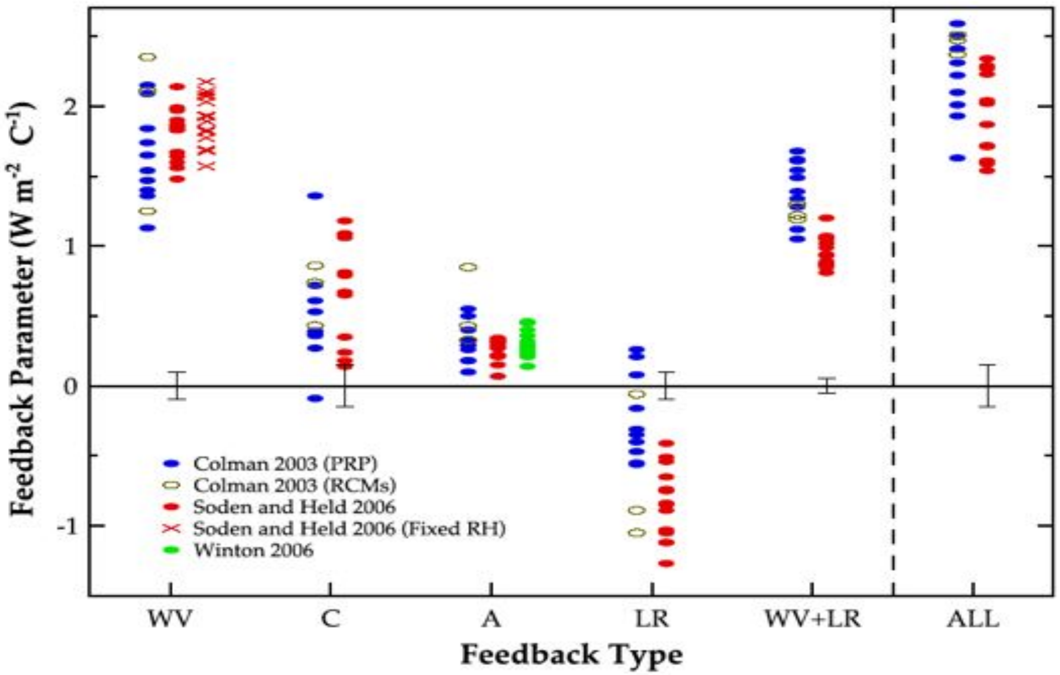


Figure 8.14. *Comparison of GCM climate feedback parameters for water vapour (WV), cloud (C), surface albedo (A), lapse rate (LR) and the combined water vapour plus lapse rate (WV + LR) in units of W m^{-2} °C^{-1}. 'ALL' represents the sum of all feedbacks. Results are taken from Colman (2003a; blue, black), Soden and Held (2006; red) and Winton (2006a; green). Closed blue and open black symbols from Colman (2003a) represent calculations determined using the partial radiative perturbation (PRP) and the radiative-convective method (RCM) approaches respectively. Crosses represent the water vapour feedback computed for each model from Soden and Held (2006) assuming no change in relative humidity. Vertical bars depict the estimated uncertainty in the calculation of the feedbacks from Soden and Held (2006).*

Even in models the feedback parameters are not easy to diagnose!

Feedback parameters from models

The water vapour feedback and the lapse rate feedback are strongly anti-correlated and usually combined into one feedback “water vapour feedback”. The best value from the models is:

$$\lambda_{H2O} = \frac{1}{1 - \beta_{H2O} - \beta_{LR}} \sim 1.5$$

1990: “The best understood feedback mechanism is water vapor feedback, and this is intuitively easy to understand” 1st IPCC.
1992: “There is no compelling evidence that water vapor feedback is anything other than positive—although there may be difficulties with upper tropospheric water vapor” IPCC supp. material.
1995: “Feedback from the redistribution of water vapor remains a substantial source of uncertainty in climate models—Much of the current debate has been addressing feedback from the tropical upper troposphere” 2nd IPCC.

Climate Sensitivity

$\lambda = \Delta T / \Delta F$ with all feedbacks= **[0.4-1.2]** $K/W/m_2$

This corresponds to a equilibrium temperature for a doubling of CO2 of about ΔT_{2CO_2}=**[1.5-4.5] K**

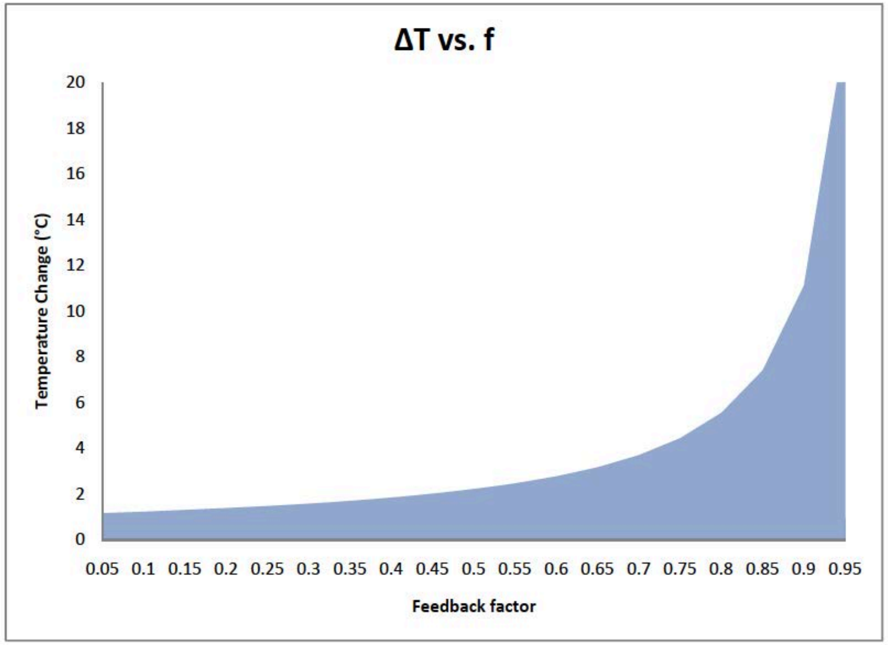


Fig 8- Changes in temperature (with a forcing equivalent to a doubling of carbon dioxide) as a function of the feedback factor

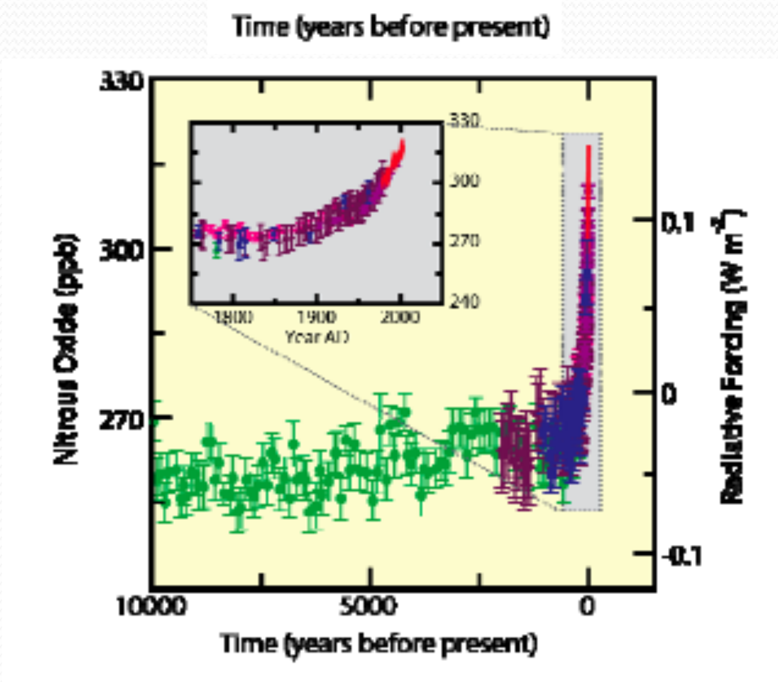
<< Unfortunately uncertainties matter a lot, in particular when the sum of the β (here f) approaches 1

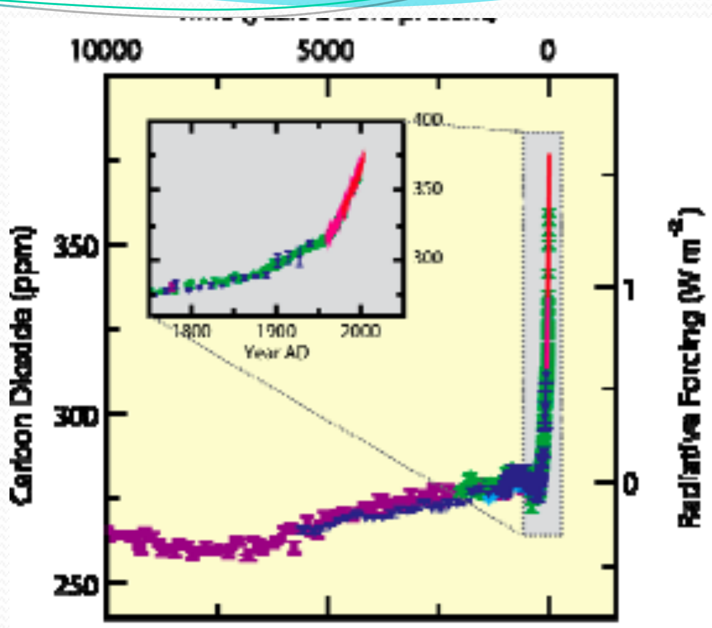
How to constrain these uncertainties with paleo observations?

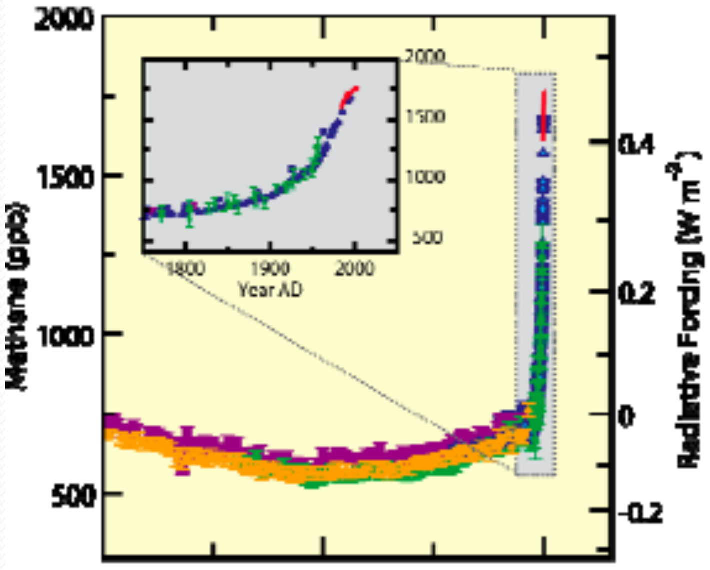
The Forcing – 1) The greenhouse gases

Measurements of gas inclusions in different Antarctix ice core (Siple Dome, Taylor Dome, Law Dome, etc.)

On the left axes the radiative forcing (defined as the energetic disequilibriul at the tropopause level) is shown in W/m2



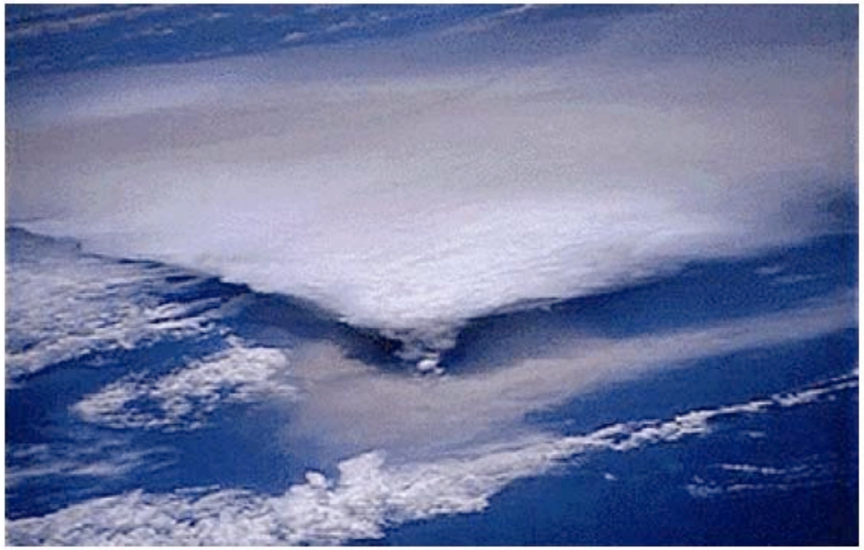




The Forcing – 2) Volcanic Activity

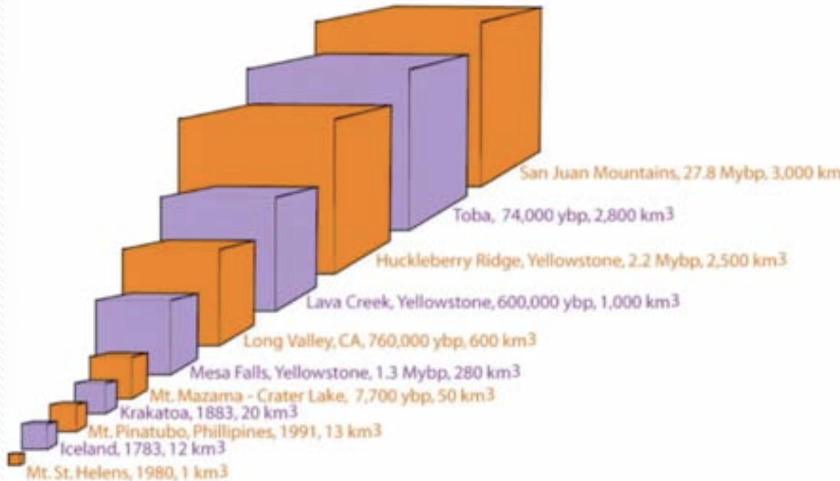
Mt. St Helens (1980)
“the beginning of
moden volcanology”

Very small climatic
effect climatic



Ausbruch des Rabaul, Papua Neuguinea
Bild: Space Shuttle Discovery, 09/19/94, STS-64 (STS64-116-064)

Rabaul, Papua Neuguinea
(1994) Volcan Tropicale



The Forcing – 2) Volcanic Activity

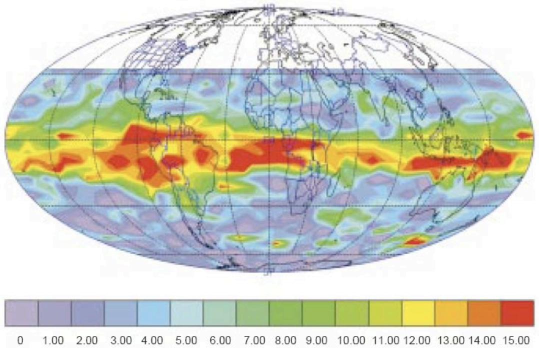
What is the climatic impact of volcanoes on climate?

-Volcanic ashes can rise up to the stratosphere but even then disappear quite rapidly.

-Different gases, in particular SO_2 ,are transformed by a chain of chemical reactions into aerosols. Once they arrive get into the stratosphere they survive several years.

The Forcing – 2) Volcanic activity

Prozesse

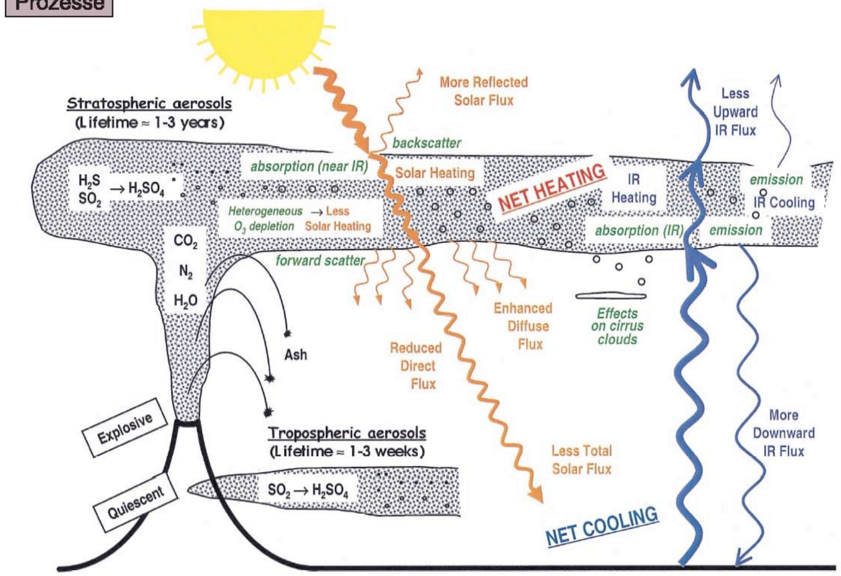


SO2 Wolke nach dem Pinatubo-Ausbruch (Read et al. 1993)

Prozesse

Sunset over Lake Mendota in Madison, Wisconsin, in May 1983, one year after the El Chichon eruption. Photograph by A. Robock (Robock, 2000)

Prozesse



(Robock, 1999)

TABLE 3. Effects of Large Explosive Volcanic Eruptions on Weather and Climate

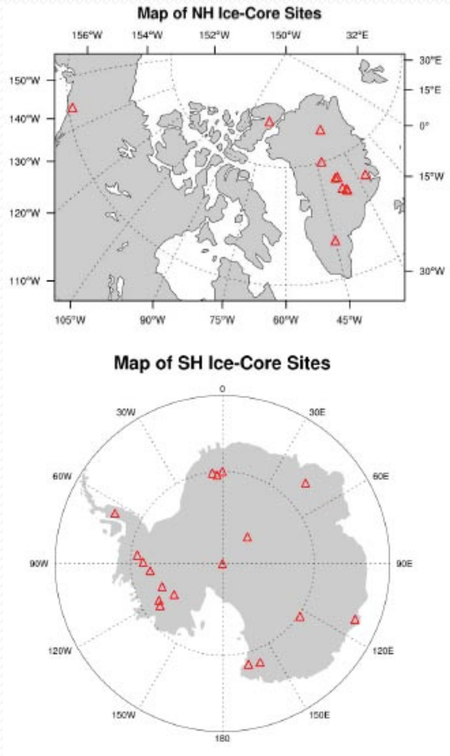
Effect	*Mechanism*	*Begins*	*Duration*
Reduction of diurnal cycle	blockage of shortwave and emission of longwave radiation	immediately	1–4 days
Reduced tropical precipitation	blockage of shortwave radiation, reduced evaporation	1–3 months	3–6 months
Summer cooling of NH tropics and subtropics	blockage of shortwave radiation	1–3 months	1–2 years
Stratospheric warming	stratospheric absorption of shortwave and longwave radiation	1–3 months	1–2 years
Winter warming of NH continents	stratospheric absorption of shortwave and longwave radiation, dynamics	$\frac{1}{2}$ year	one or two winters
Global cooling	blockage of shortwave radiation	immediately	1–3 years
Global cooling from multiple eruptions	blockage of shortwave radiation	immediately	10–100 years
Ozone depletion, enhanced UV	dilution, heterogeneous chemistry on aerosols	1 day	1–2 years

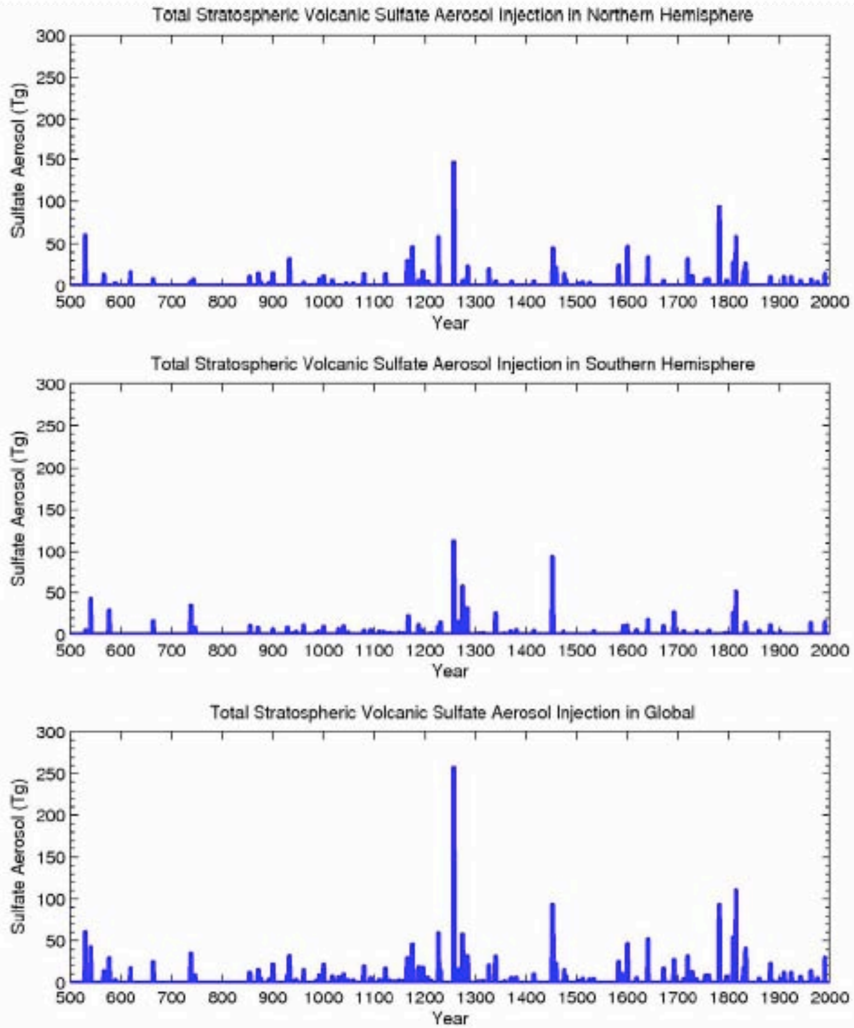
(Robock 1999)

Heating of the stratosphere by IR absorbtions.
Cooling of the troposphere by reflection of solar radiation.

The Forcing – 2) Volcanic Activity

How quantifying volcanic eruptions in the past?



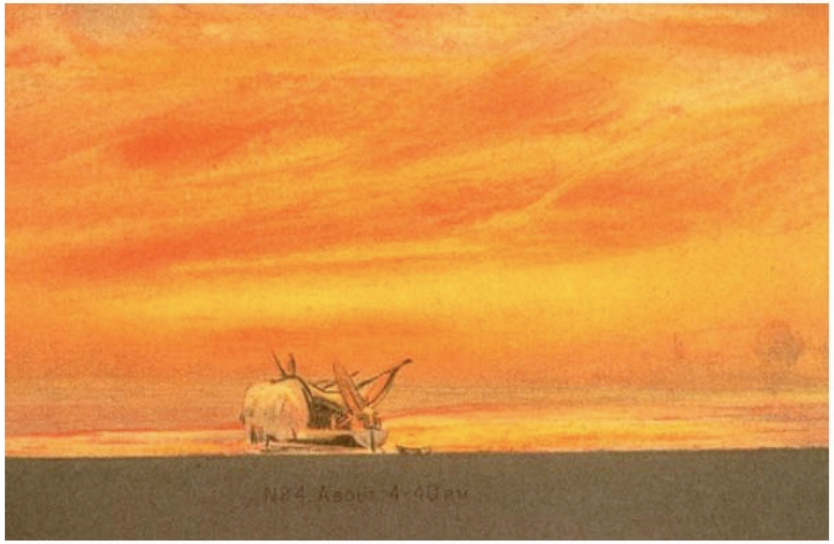


GAO,Robock,Ammann,GRL, 2008

The Forcing – 2) Volcanic Activity

How quantifying volcanic eruptions in the past?

William Ascroft, Sunset, Chelsea, London, November 26, 1883, three months after the eruption of Krakatoa (Courtesy of Peter Francis).



Zerefos et al., Atmosph.Chem. and Phys., 2007

Examples of "volcanic" and "non-volcanic" paintings considered in the paper

Fig. A1. Example of a non-volcanic sunset, painted by J.M.W. Turner entitled "The Lake, Petworth, Sunset", created in 1828, with R/G ratio of 1.14±0.04 (see Tate Gallery at http://www.tate.org.uk/servlet/ViewWork?cgroupid=999999996{\&}workid=14876).

Fig. A2. Example of volcanic sunset by J. M. W. Turner entitled "Sunset" (c.1833) with R/G ratio of 1.76±0.03, that illustrate the optical phenomena due to the eruption of Babuyan (1831) (see Tate Gallery at http://www.tate.org.uk/servlet/ViewWork?cgroupid=999999996{\&}workid=14820).

The Forcing – 2) Volcanic Activity

How quantifying volcanic eruptions in the past?

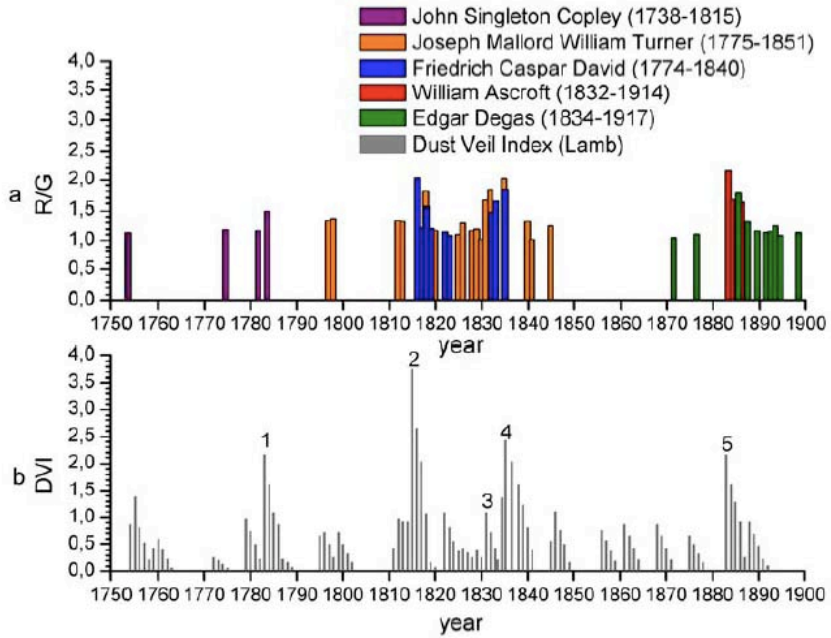


Fig. 1. **(a)** The variation of the chromatic ratio R/G that correspond to paintings of Copley, Turner, David, Ascroft and Degas. **(b)** The Dust Veil Index. The numbered peaks are 1. Laki, 2. Tambora, 3. Babuyan, 4. Coseguina and 5. Krakatau.

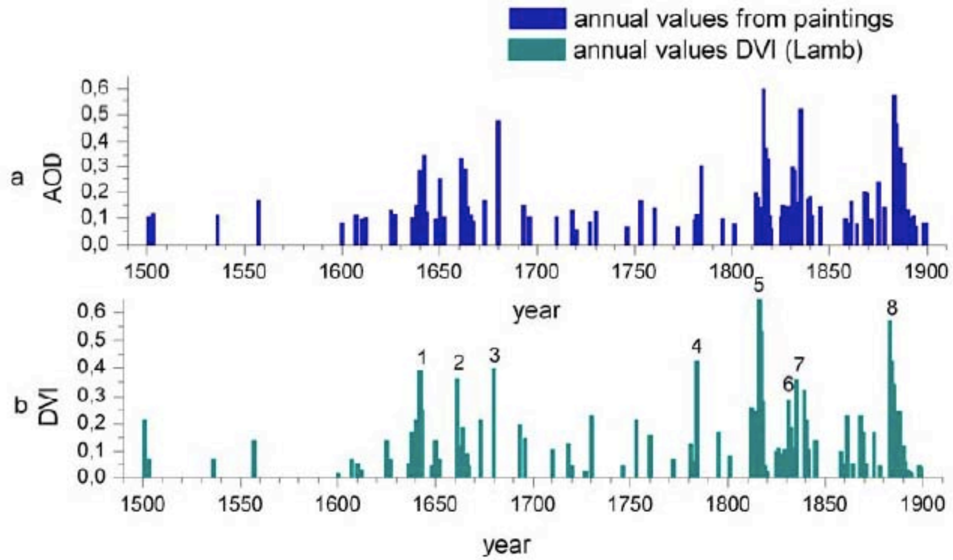


Fig. 5. **(a)** The aerosol optical depth at 550 nm as estimated from paintings and model calculations. **(b)** The corresponding Dust Veil Index. The numbers on the DVI histogram refer to the same major volcanic eruptions outlined in Fig. 2.

Zerefos et al., Atmosph.Chem. and Phys., 2007

The Forcing – 3) Solar Activity

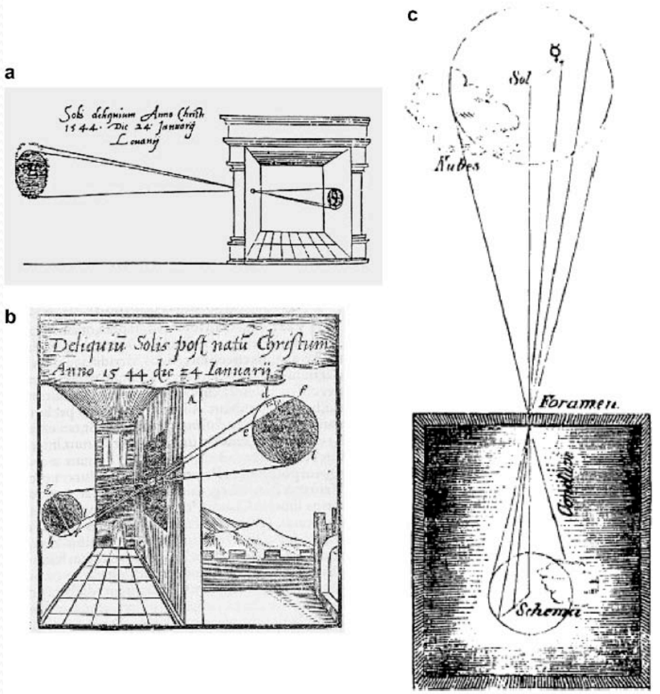
First observation of sun spot 2000 years BP

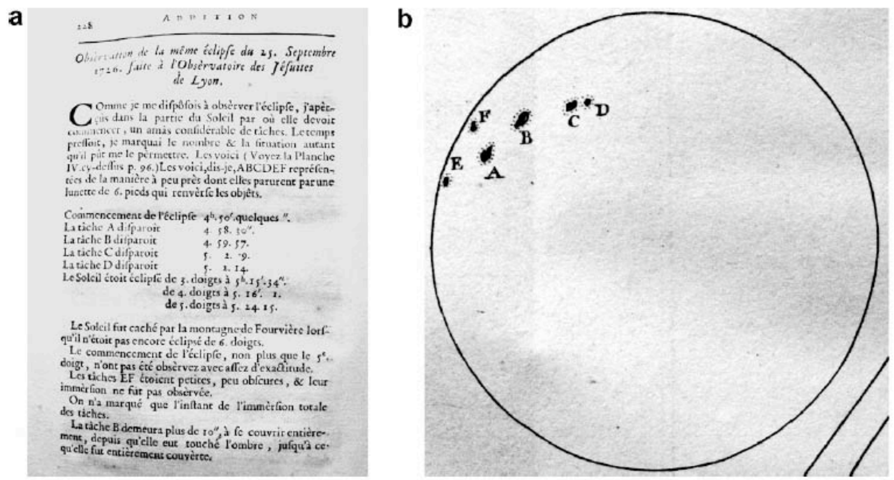
En Europe Galilei started in 1612

XIII. *Observations tending to investigate the Nature of the Sun, in order to find the Causes or Symptoms of its variable Emission of Light and Heat; with Remarks on the Use that may possibly be drawn from Solar Observations. By* William Herschel, *L.L.D. F.R.S.*

Read April 16, 1801.

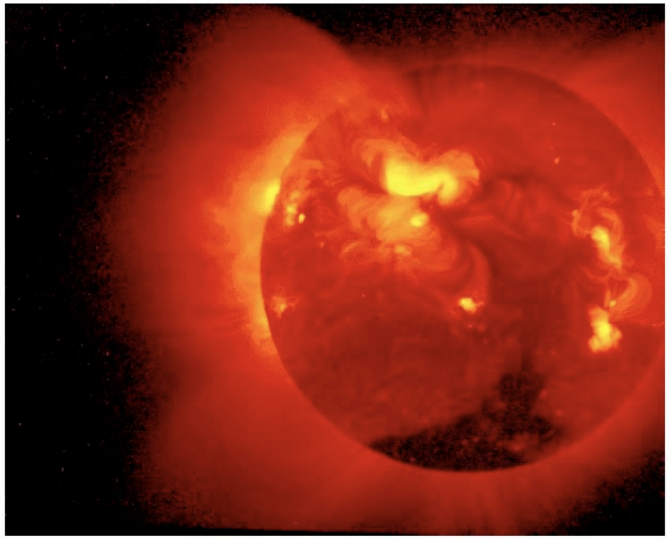
On a former occasion I have shewn, that we have great reason to look upon the sun as a most magnificent habitable globe; and, from the observations which will be related in this Paper,

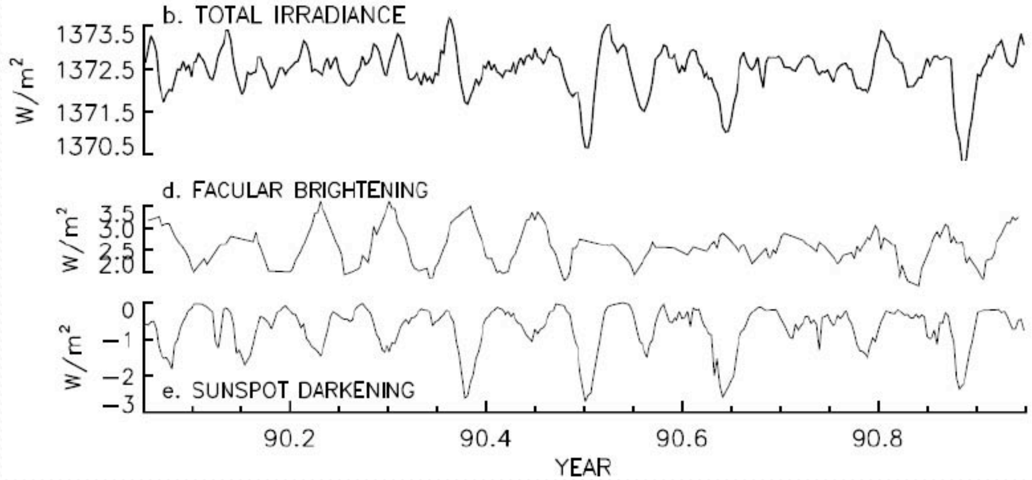


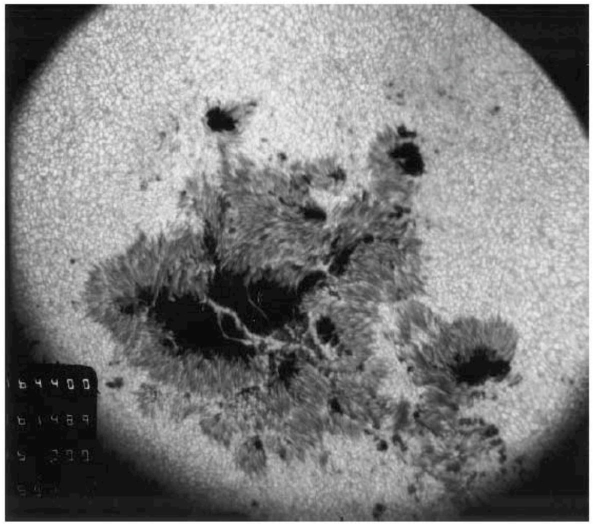


The Forcing – 3) Solar Activity

Die Sonne im Röntgenteleskop

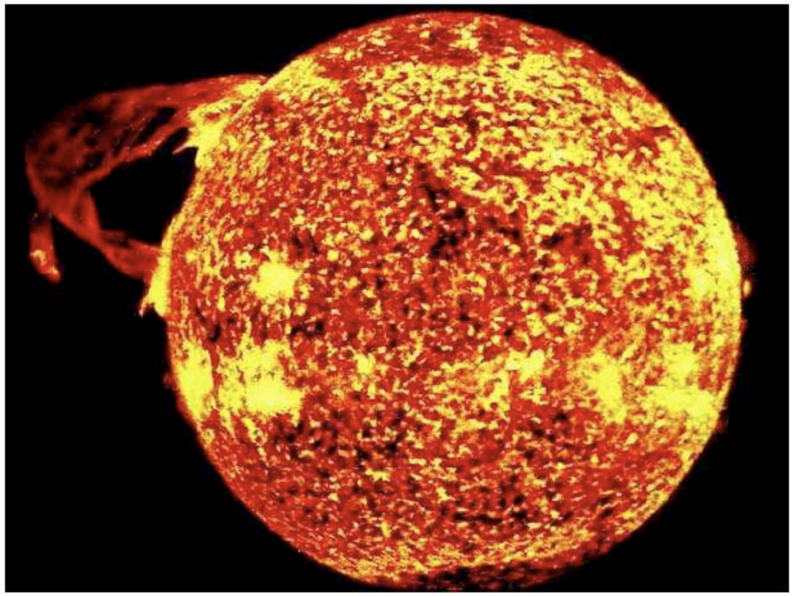




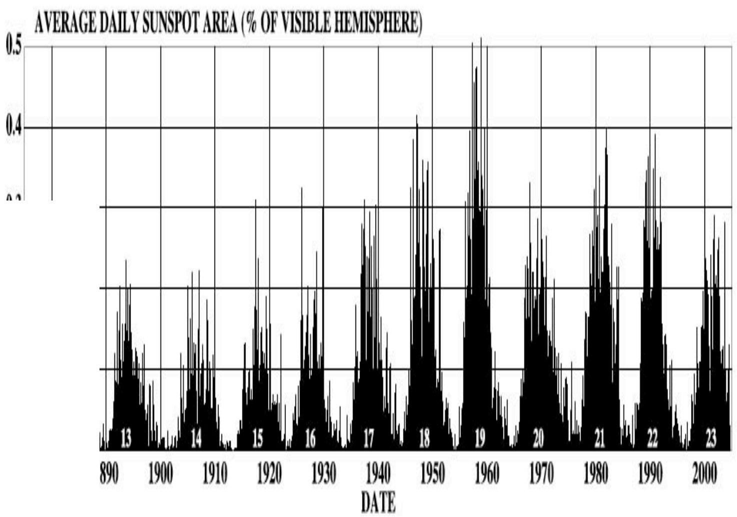


Sonnenfleck, 1989, Big Bear Solar Observatory, CA

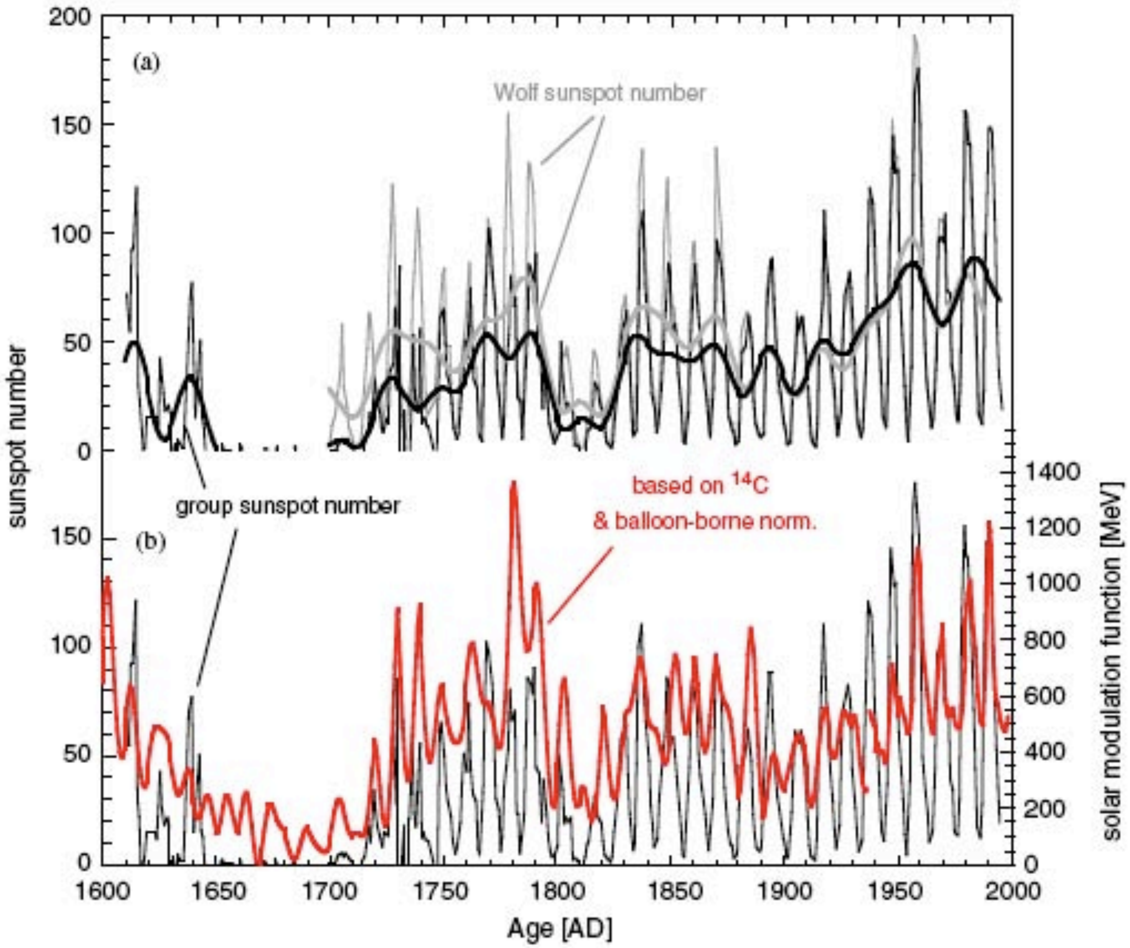
Sonnenfackel



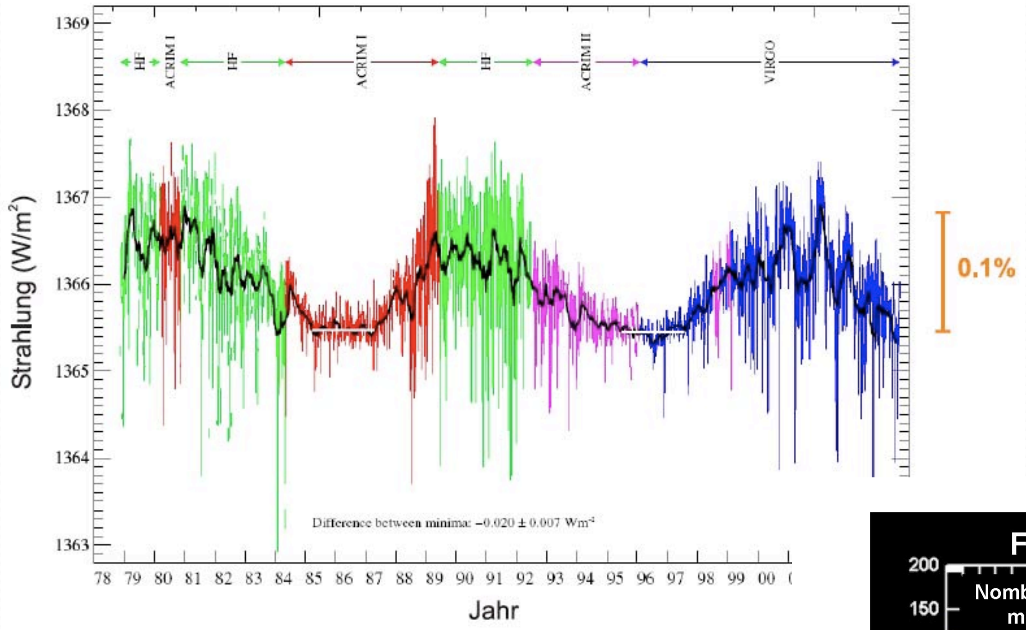
The Forcing – 3) Solar Activity

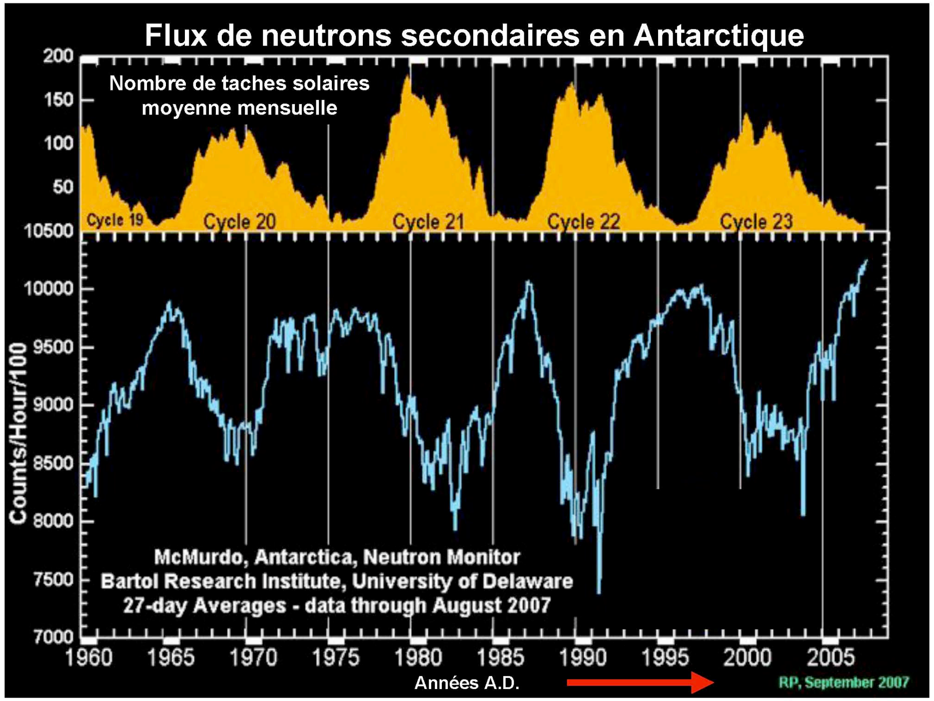


Greenwich Observatory

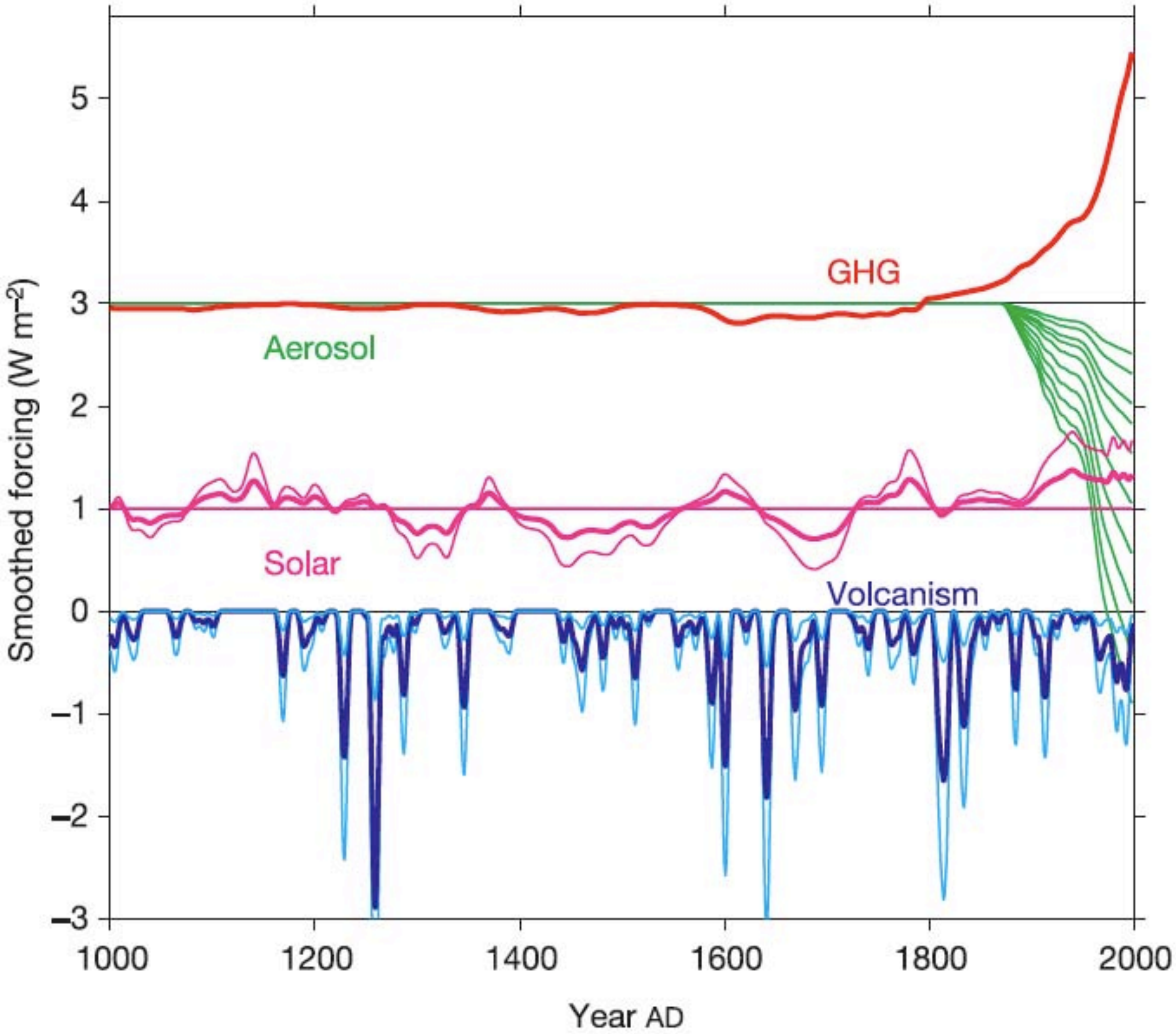


The Forcing – 3) Solar Activity





The Forcing



All forcing terms are in W/m2

Greenhouse gases

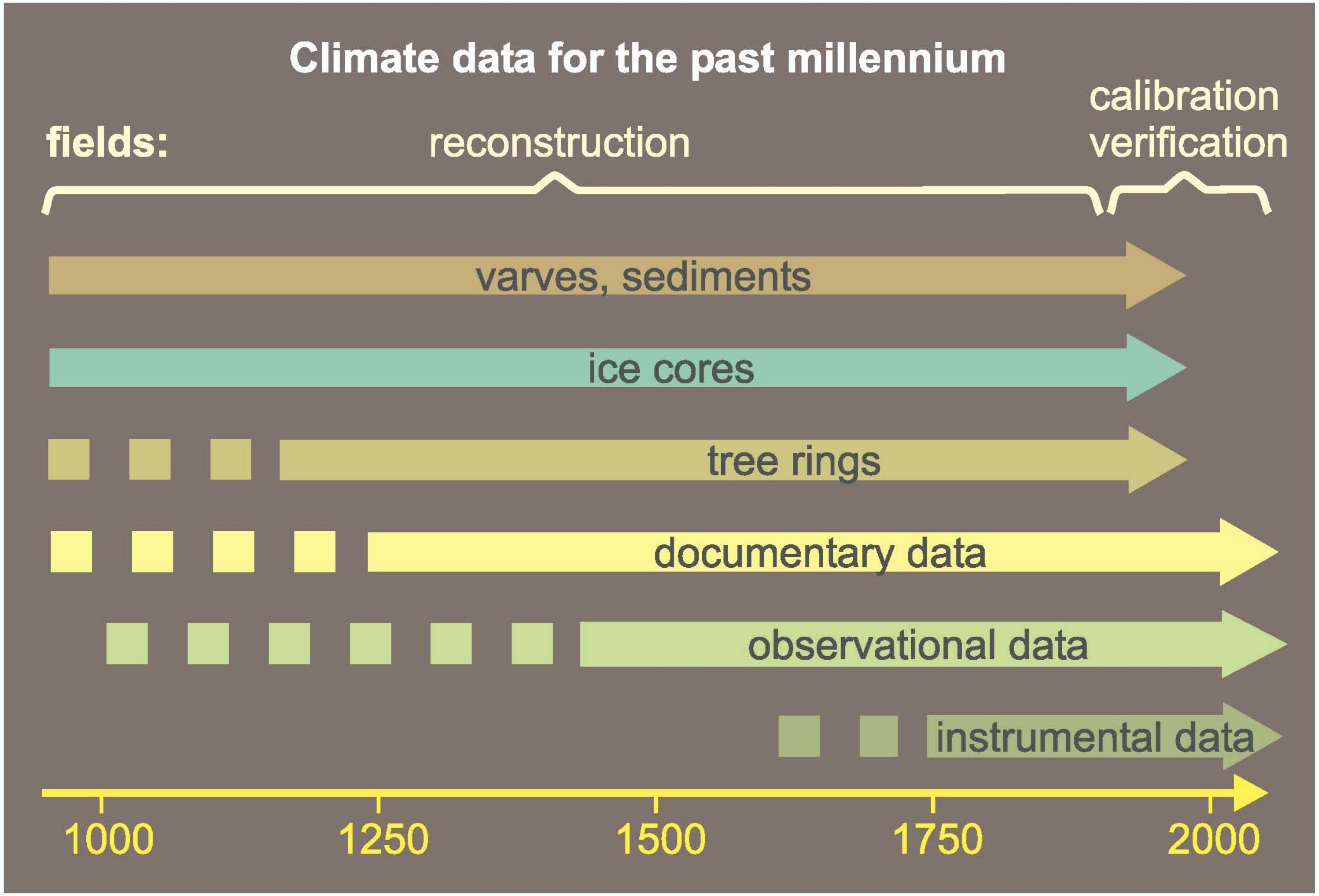
Industrial Aersosole

Solar activity

Volcanic aerosols

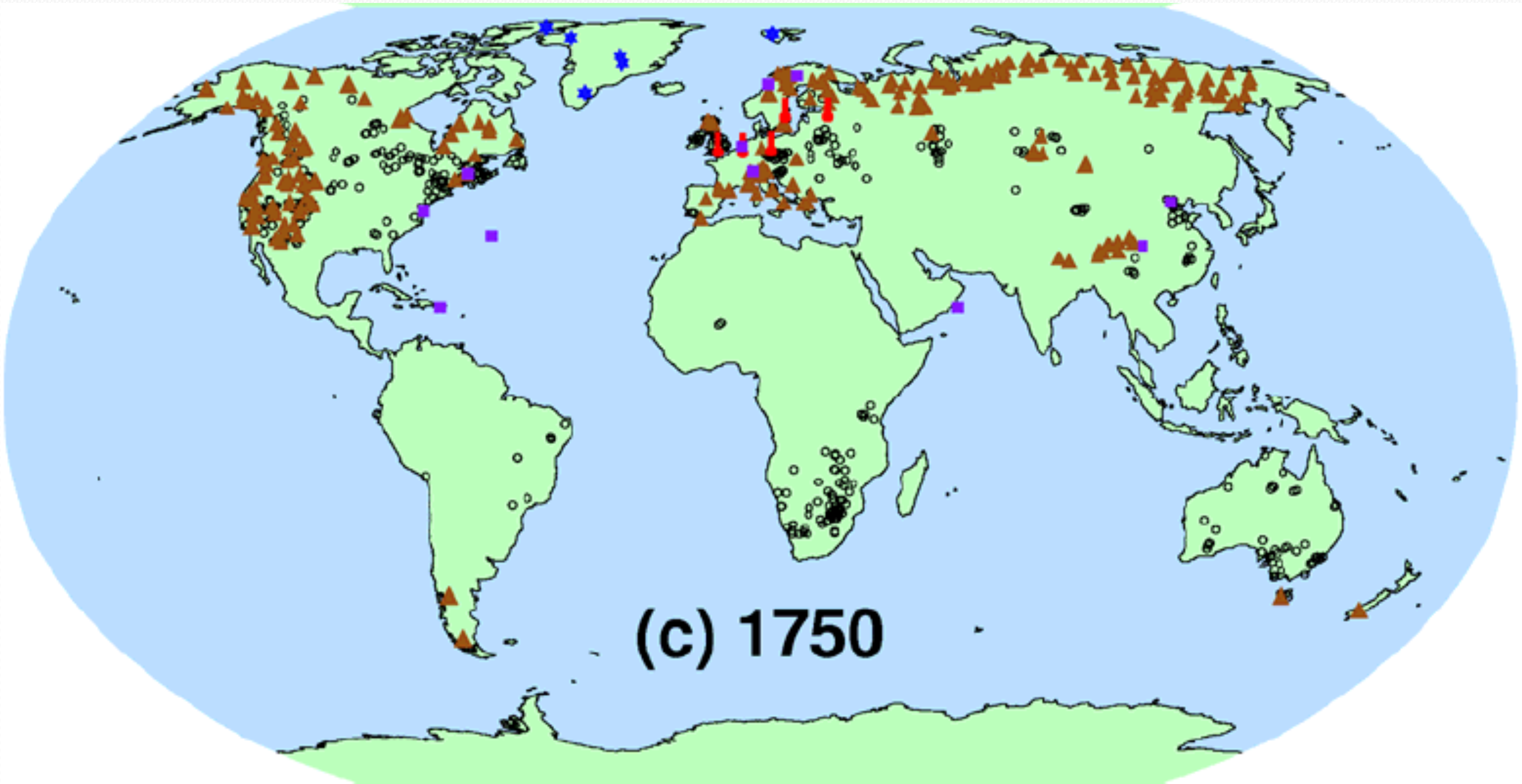
Climate of the past millenium

Methoden



- Instrumental data: red
- Tree rings: brown
- Forests: black
- Ice cores: blue
- Autres : violet

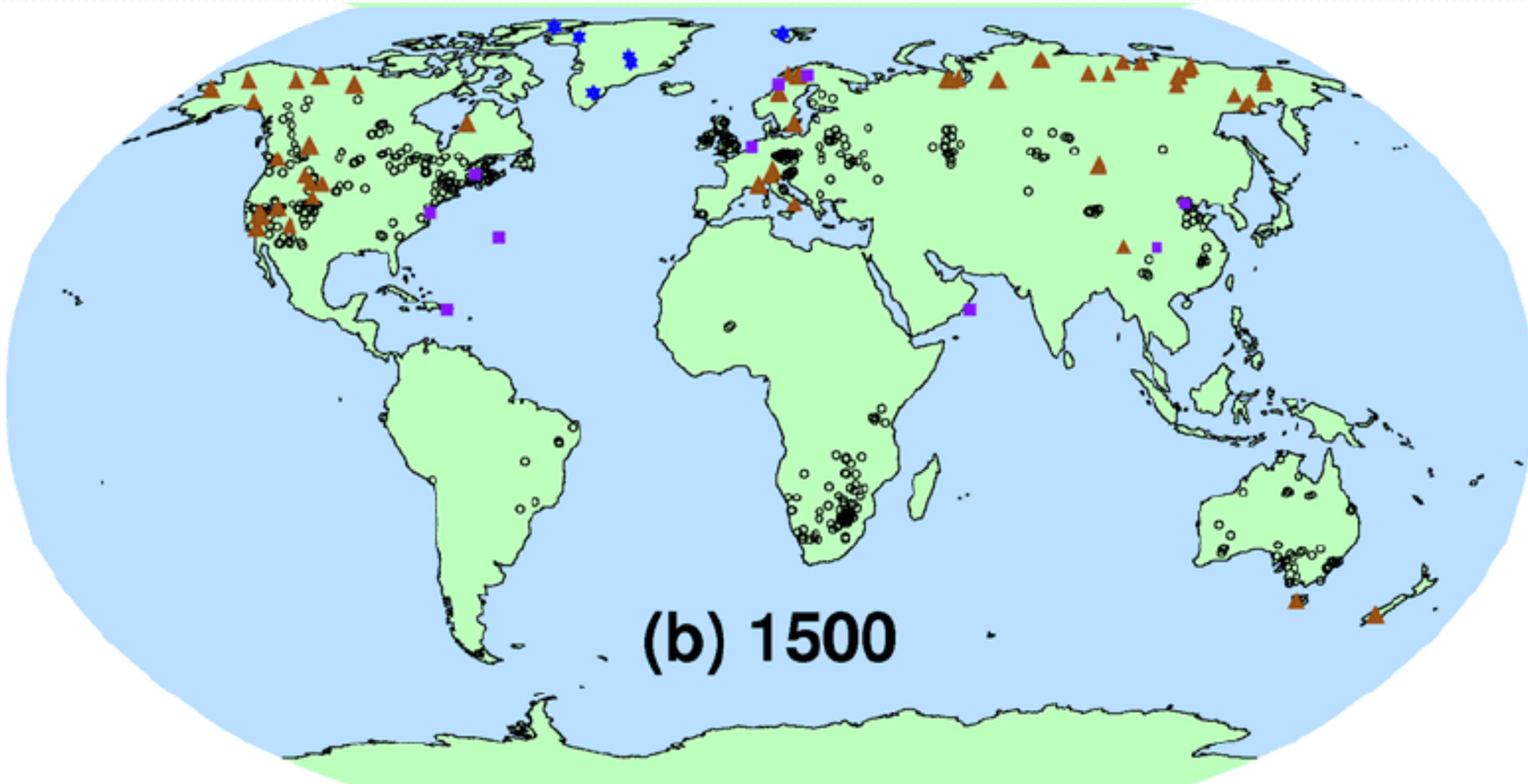
Proxy sites sensitive to temperature until 1750



Quatrième rapport GIEC, 2007

- Instrumental data: red
- Tree rings: brown
- Forests: black
- Ice cores: blue
- Autres : violet

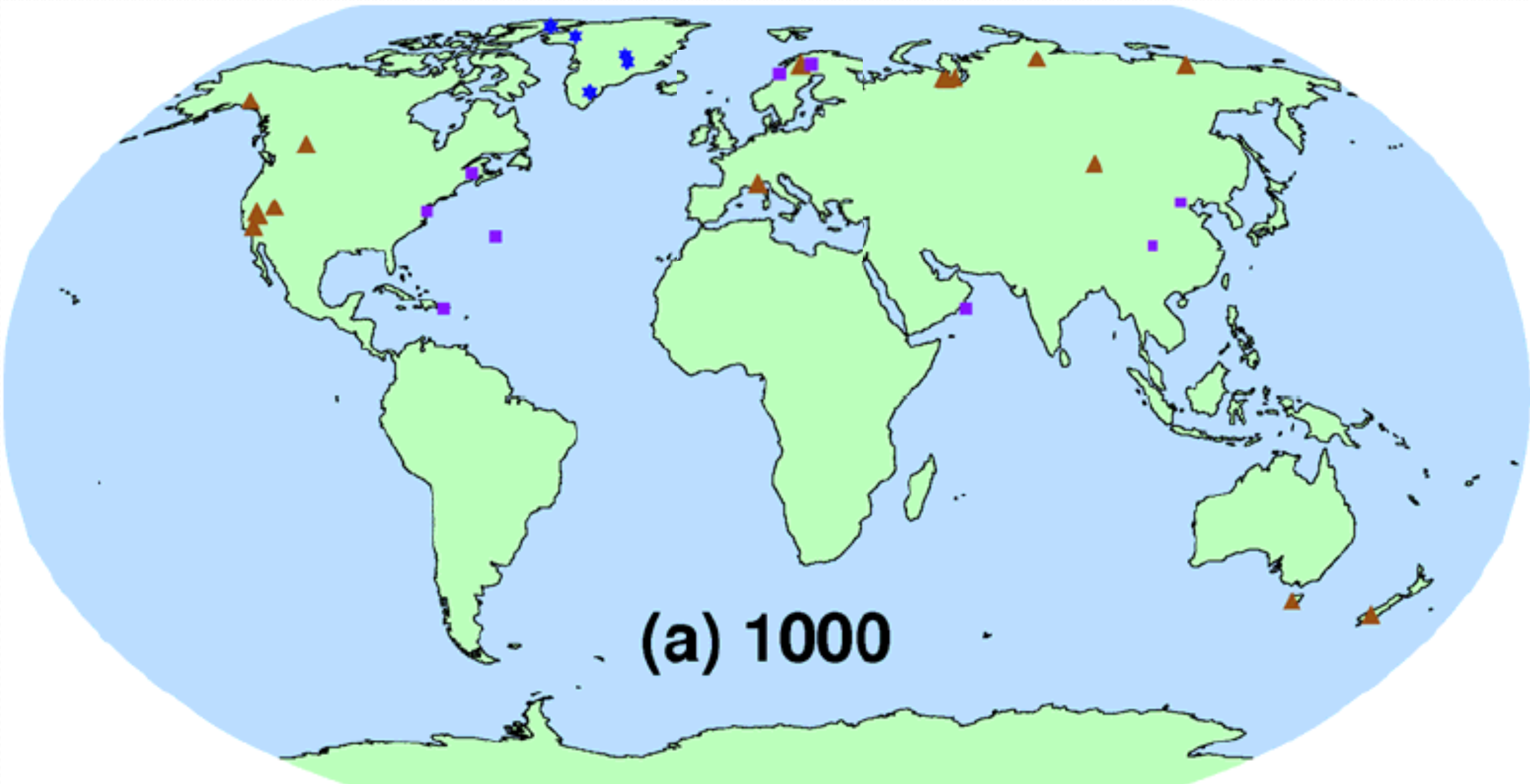
Proxy sites sensitive to temperature until 1500



Quatrième rapport GIEC, 2007

- Tree rings: brown
- Ice cores: blue
- Autres : violet

Proxy sites sensitive to temperature until 1000



Quatrième rapport GIEC, 2007

Estimation of climate sensitivity based on millenial climate reconstructions

A direct calculation of climate sensitivity is of course not possible (no steady state).

Monte Carlo runs with simplified climate models (EBMs or EMICs) varying the respective forcings (solar, volcanic, GHGs) within their estimated uncertainties (sometimes also model parameters such as ocean diffusivity).

A measure of goodness of each simulation is constructed based on the comparison with the different temperature reconstruction and a probability density function for the respective climate sensitivities is computed based on a Bayesian approach.

> Importance of the Bayesian prior!

Climate sensitivity for different millenial reconstructions

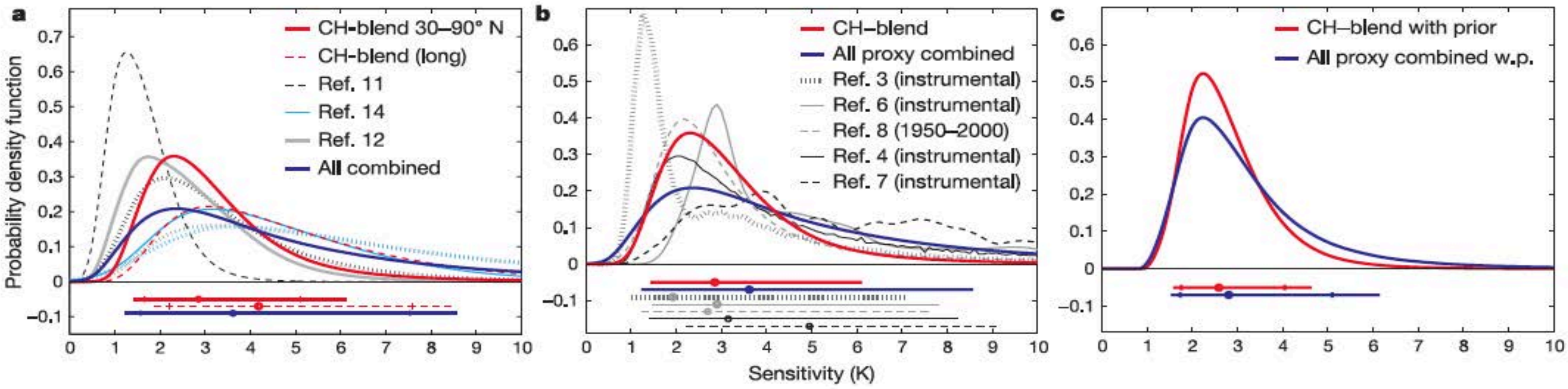
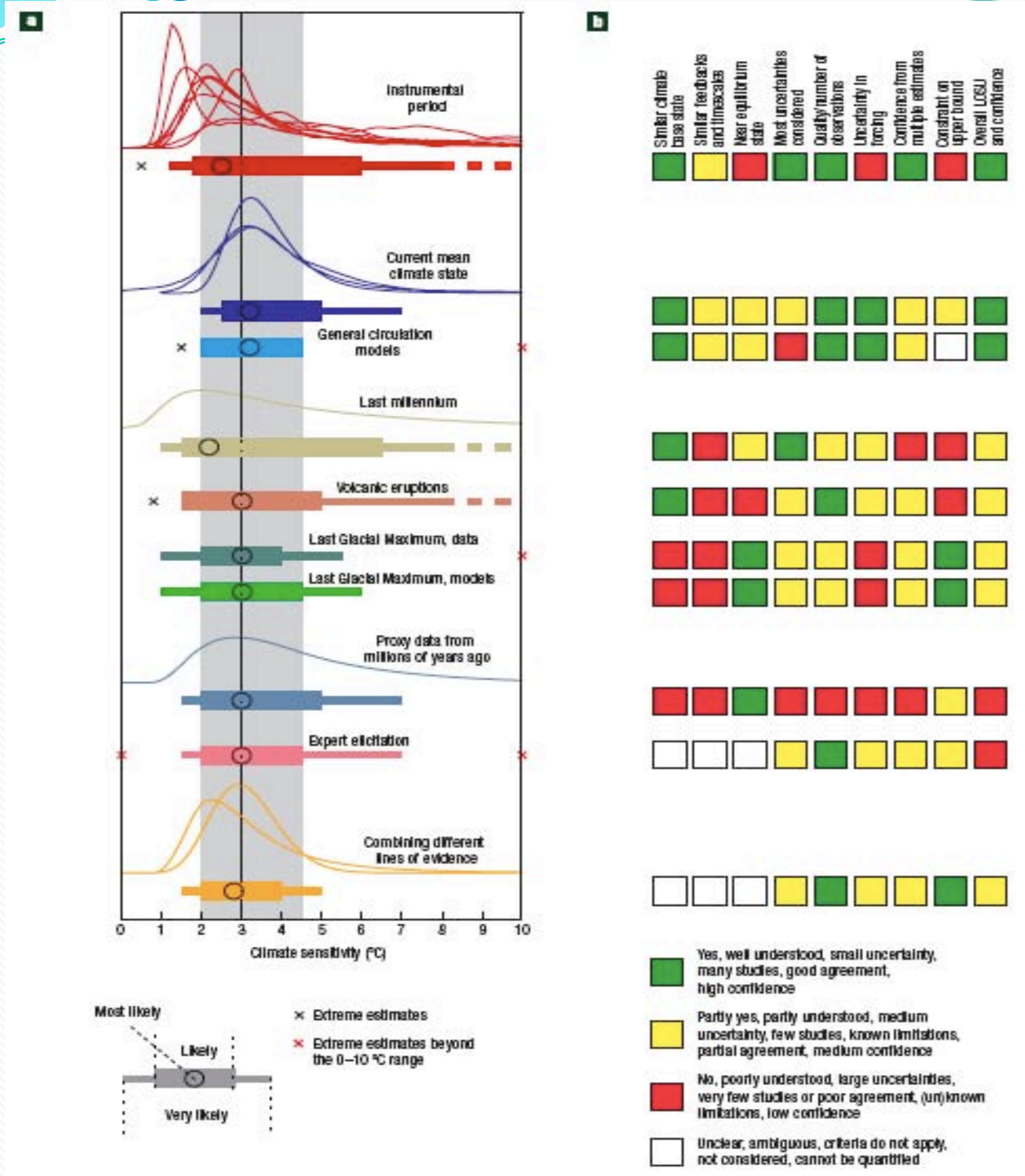


Figure 3 | Estimated probability density functions (PDFs) for equilibrium climate sensitivity to CO_2 doubling (in K). a, PDFs from a range of palaeoreconstructions using data to 1850 (dotted lines, based on rescaled data). The horizontal bars indicate the 5–95% range of PDFs (median is indicated by a dot, and 10th and 90th percentiles by a vertical bar). **b**, Comparison to other estimates of climate sensitivity based on instrumental data[3,4,6,7] over the twentieth century or 1950–2000[8]. All PDFs have been scaled to integrate to 1 between 0 and 10 for better comparison. **c**, Combined estimate using a result from instrumental data[8] as prior distribution, updated by the result from pre-industrial data ('w.p.').

1030

- Of course lowest CS for flattest temperature reconstruction such as Mann's hockeystick (feel the irony)
- The prior in the Bayesian computation makes big difference in particular for high CS
- AR5: Has its own millenial chapter, there is a new forcing data set (Schmidt et al. 2009) and many more simulations

Climate Sensitivity based on different methods



Climate sensitivity, CS, estimated based on reconstructed climate variations during the last millenium.

1) CS slightly lower than the other estimation
2) Large uncertainties!

Knutti and Hegerl, Nature, 2008

Climate sensitivity based on the LGM

Old classics: Genthon, 1987, Lorius, 1990

- Based exclusively on ice core data, rough estimate of polar amplification (ΔT_{Vostok}=6°C > ΔT_{Glob}=4-5°C).
- Multivariate analysis (no computation of the individual radiative forcings), GHGs explained about 2°C of LGM temperature change.
- CS for doubled CO2 lies within 3-4°C, ie CS factor of ~3.

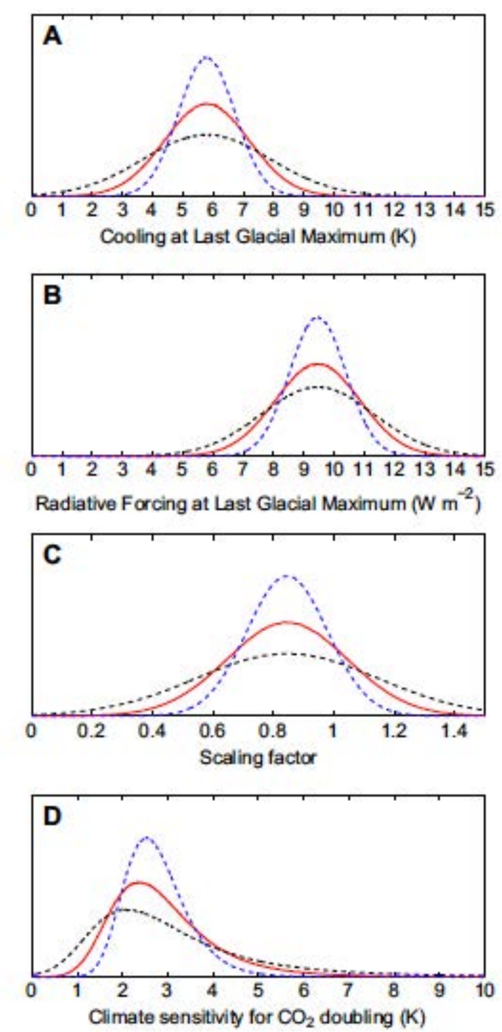
- Problems: Independence of the parameters in the multivariate analysis, missing forcings, mixture of slow and fast (Charney) processes.

Climate sensitivity based on the LGM

Most recents studies of LGM data based CS estimation:
Koehler et al. QSR 2009
Full list of radiative forcings ΔR partly using models

	ΔR in W/m2
GHGs	2.8
ice sheet	3.2
sea level	0.6
snow	0.8
sea ice	2.1
Vegetation	1.1
Dust	1.9
Total	12.4
Charney	9.5
ΔT without feedbacks	3.8K cooler

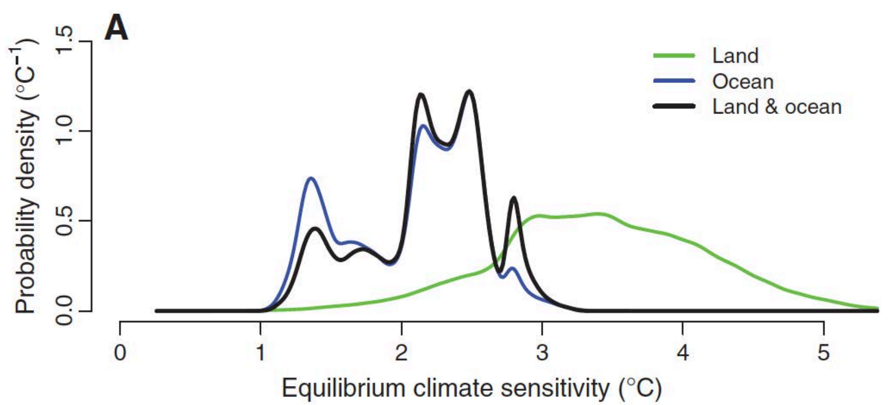
Clear tendancy to smaller CS based on LGM data. Here for example 2.4K for 2*CO2 which is already assuming lower CS for the LGM



- Uncertainties in ocean proxies (foraminifera transfer functions vs UK37) make at least 1°C uncertainty.
- Time varying climate sensitivity, here eg 15% lower glacial CS
- Unaccounted effects

Climate sensitivity based on the LGM

Model based approach as for the millenial variations.
> Schneider von Deimling, 2006, Schmittner 2012



> Apparently completely different estimates of CS based on land data on one hand and ocean data on the other hand. Problems with the land/sea contrast?

- Relatively small CS of 2.3°C, very small uncertainty range 1.7-2.6K for the 66% probability range
- Strength: Newest data sets using spatial information
- Critics: The model has not a realistic representations of clouds, unaccounted uncertainties, not discussing non-linearity of CS

My guess what will appear in the AR5

More data/model merging type of analysis.

Smaller uncertainty range for high climate sensitivities (5°C for 2*CO2 ?).

Slightly lower median CS based the paleo analysis (2.5°C?).